Early W primes at the LHC

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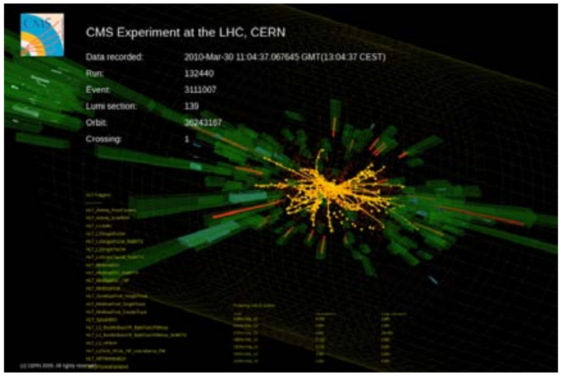
Outline

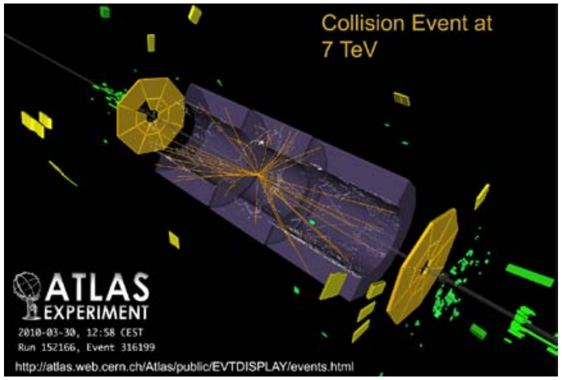
1. Constructing W primes for the early LHC
   - Introduction to W primes - Why should we care?
   - What type of W primes do we consider?
   - Effective Lagrangian Approach to EWPC
2. Discussion of Models
   - Isotriplet of Heavy Gauge Bosons
   - Left-Right Model with Bifundamental Higgs
   - LR Model with Single Higgs Doublet
3. Odds and Ends

Why care about W primes?

LHC collisions at 7 Tev $\Rightarrow$ Potential to discover new physics:

- GUTs
- UED
- Little Higgs
- ...





A large subset of BSM theories introduces new, massive gauge bosons $\rightarrow$ observable at LHC? W's are promising candidates:

- Single particle resonance $\rightarrow$ Large cross section
- Low background in leptonic channels $\rightarrow$ Easy discovery
- Complete mass reconstruction in hadronic channnels ($t\bar{b}$)

Z primes and W primes

Conventional wisdom: (*e.g.* PDG review on W primes)

"A generic property of all these gauge theories is that besides a W' they contain at least a Z' boson, whose mass is typically comparable or smaller than $M_{W'}$."

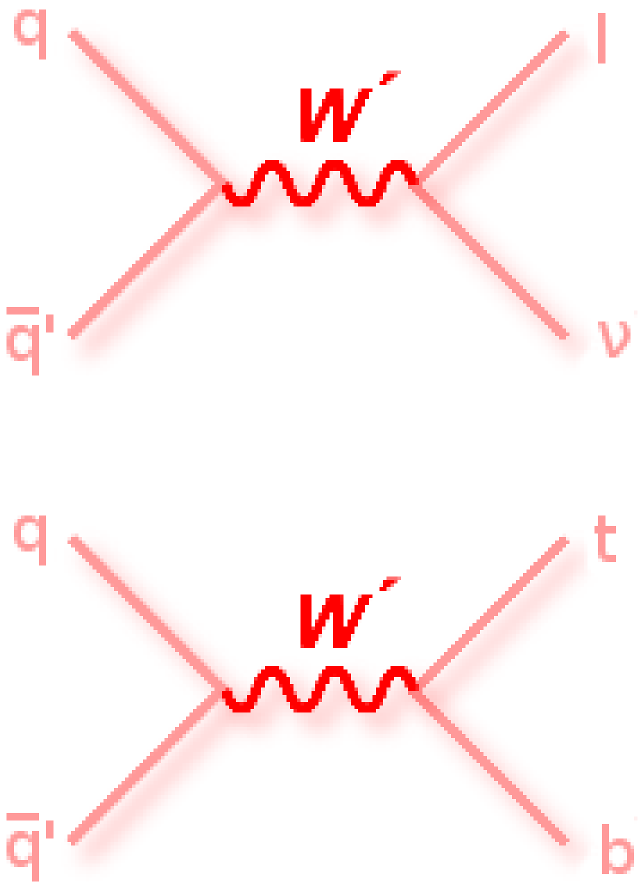
The usual conclusions:

- The strong bounds on Z' indirectly also apply to W'.
- Z's are likely to be found before W's.

Questions we want to answer:

- Is this argument unavoidable?
- What are the conditions for a light W' without a Z'?

Our definition of a (relevant) W' Boson



Focus is on early LHC physics
$\Rightarrow$ Define "interesting" W's as:

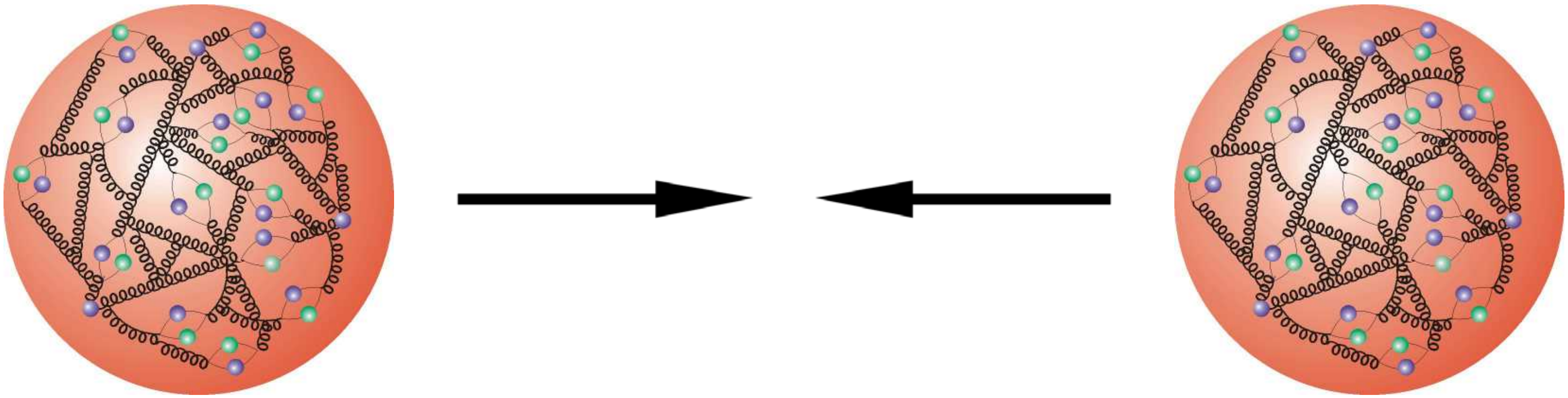
1. Electric charge
2. Massive (Tevatron: TeV scale)
3. Spin 1 $\Rightarrow$ gauge boson
4. Color-neutral
5. Coupled to LHC initial state
6. Decay to $\ell\nu$ (and $t\bar{b}$)

This excludes:

- Heavy resonance decay to W'
- $W' \rightarrow$ EW gauge bosons

Restrictions from Initial State: $pp \to W'$

Producing a charged, color-singlet state from pp collision:



	gg	$gq/g\bar{q}$	$qq/\bar{q}\bar{q}$	$q\bar{q}$
Color singlet?	☺	☹	☹	☺
$Q = T_3 + Y \neq 0$?	☹	☺	☺	☺

List of Quark-Antiquark Couplings

Quark fields:

	color	$SU(2)_L$	Y
Q	3	2	1/6
$u^{c\dagger}$	3	1	2/3
$d^{c\dagger}$	3	1	-1/3

Antiquark fields:

	color	$SU(2)_L$	Y
$Q^\dagger$	$\bar{3}$	$\bar{2}$	-1/6
u^c	$\bar{3}$	1	-2/3
d^c	$\bar{3}$	1	1/3

Color-neutral initial state operators with electric charge:

1. $Q^\dagger \sigma^a Q$: triplet, contains $Q = 0, \pm 1$ ✔
2. $(u^c)^\dagger d^c$ (and h.c.): singlet with charge ± 1 ✔
3. Qu^c, Qd^c: doublet with charge $0, \pm 1$ ✘

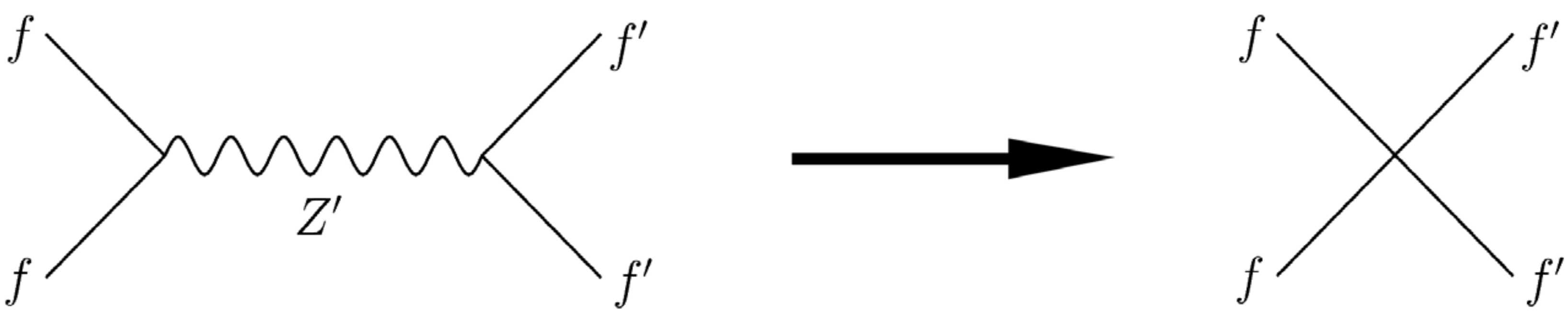
Begin Detour

Constraints On Weak Scale Effective Lagrangian

Effective theory approach to EWP and LEP II constraints:

- Find couplings of SM quarks, charged leptons, and Higgs boson to Z' boson
- Integrate out neutral currents
- Obtain coefficients of induced dimension 6 operators

e.g.



EWP and LEP II Constraints - List of Experiments

Previous work by W. Skiba and Z. Han[1]:
EWP and LEP II constraints on 21 dimension 6 operators

- Atomic parity violation (Weak charge of Cs and Tl)
- DIS (ν nucleon from NuTeV, CDHS, CHARM, CCFR, ν e from CHARM II)
- Z-pole (Z width, hadronic cross section, ratios of decay rates, FB asymmetries, hadronic charge asymmetries, polarized asymmetries)
- Fermion pair production at LEP II (total cross-sections and FB asymmetries in $e^+e^- \to f\bar{f}$, differential cross section for $e^+e^- \to e^+e^-$
- W mass, differential cross section for $e^+e^- \to W^+W^-$

[1] Phys.Rev. D71 (2005) 075009

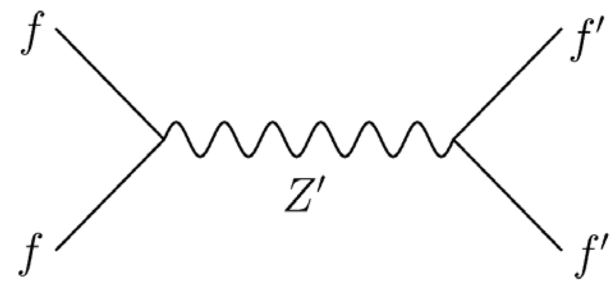
Four Fermion Operators

List of dimension six operators relevant for our discussion:

1. Four fermion singlet operators:

   $\mathcal{O}^{s}_{ff'} = (f^{\dagger}\bar{\sigma}_{\mu}f)\,(f'^{\dagger}\bar{\sigma}^{\mu}f')$

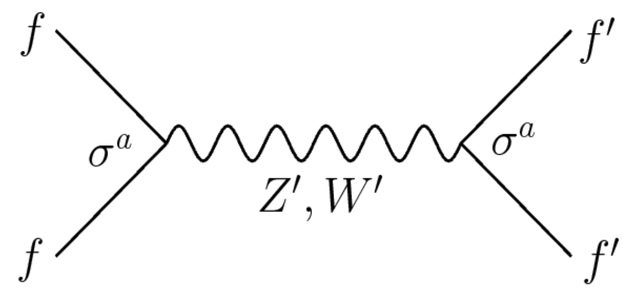
   (exchange of $SU(2)_L$ singlet Z')



2. Four fermion triplet operators:

   $\mathcal{O}^{t}_{ff'} = (f^{\dagger}\bar{\sigma}_{\mu}\,\sigma^{a}\,f)\,(f'^{\dagger}\bar{\sigma}^{\mu}\,\sigma^{a}\,f')$

   (exchange of $SU(2)_L$ triplet W'/Z')



Strongest bounds on four fermion operators $\rightarrow$ LEP II

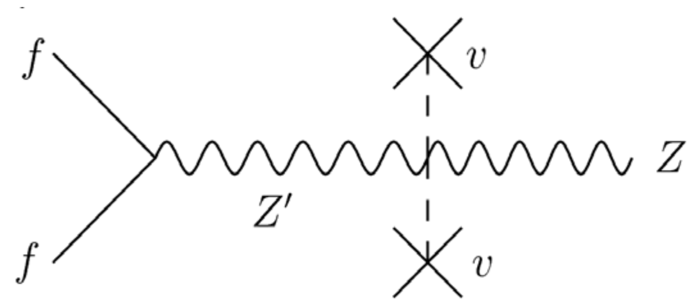
Operators with Couplings to Higgs

3. Higgs-fermion operators:

   $$\mathcal{O}_{hf} = i(h^\dagger D_\mu [\sigma^a] h) (f^\dagger \bar{\sigma}^\mu [\sigma^a] f)$$

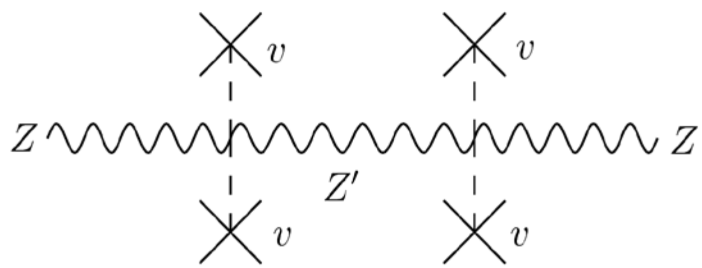
   Replace D_μ by Z boson and insert Higgs VEV

   $\Rightarrow$ Changes couplings of fermions to Z boson



4. T Parameter: $\mathcal{O}_h = |h^\dagger D_\mu h|^2$

   $\Rightarrow$ Generates mass splitting between Z and W



(S parameter is not generated at tree level)

End Detour

W prime in $SU(2)_L$ Isotriplet

First scenario: $Q^\dagger \sigma^a Q$

e.g. Little Higgs, KK gauge bosons

Symmetry breaking:

$SU(2)_1 \times SU(2)_2 \to SU(2)_L$
by VEV of bifundamental scalar

$\Rightarrow$ Isotriplet of heavy gauge bosons

- Mass splitting between Z' and W' small ($\Delta M \approx v^2/2f$)
- W', Z' coupling typically of order g
- Triplet 4 fermion operators, strong interference with SM W
- Custodial symmetry $\Rightarrow$ no T parameter

Limits on W Primes with $SU(2)_L$ Coupling

For $g_1 = g_2$, Higgs can be decoupled.

$$\Rightarrow \qquad \mathcal{L}_{\text{eff}} = -\frac{g^2}{8M_{W'}^2}\left(Q^\dagger \bar{\sigma}_\mu \sigma^a Q \pm L^\dagger \bar{\sigma}_\mu \sigma^a L\right)^2$$

if Q, L doublets live in same(+) or opposite(-) $SU(2)$s.

$$\Rightarrow \qquad M_{W'} \geq 3.3 \text{ TeV / } 2.2 \text{ TeV}$$

Cross sections for 2.2 TeV gauge bosons at the LHC (7 TeV):

$$\sigma(pp \to Z' \to e^+e^-) \approx 1.5 \text{ fb}$$
$$\sigma(pp \to W' \to e\nu) \approx 6 \text{ fb}$$

$\Rightarrow$ Both Z' and W' out of reach of first run!

W prime in $SU(2)_L$ Singlet

Second scenario: $(u^c)^\dagger d^c$ + h.c.

- W' generator doesn't commute with hypercharge
- W' and $B \in$ broken non-Abelian gauge group
- u^c and d^c belong to multiplet of this group

Simplest idea: $SU(2)_R \to U(1)_Y$

- W' with $Q = \pm 1$ and no Z'
- Incorrect fermion hypercharges ($\pm$ 1/2)

Next to simplest idea: $SU(2)_R \times U(1)_X \to U(1)_Y$

- W' and Z', can adjust hypercharges

Fermion Charges in Left-Right Model

Charges of standard model fermions:

field	X	T_R^3	Y
Q	1/6	0	1/6
$\begin{pmatrix} d^c \\ u^c \end{pmatrix}$	-1/6	$\pm 1/2$	$\begin{pmatrix} +1/3 \\ -2/3 \end{pmatrix}$
L	-1/2	0	-1/2
$\begin{pmatrix} e^c \\ \nu^c \end{pmatrix}$	1/2	$\pm 1/2$	$\begin{pmatrix} +1 \\ 0 \end{pmatrix}$

- Left-right symmetry
- $U(1)$ charges: B-L
- Anomaly free

Scalars in $SU(2)_L \times SU(2)_R \times U(1)_X$ Model

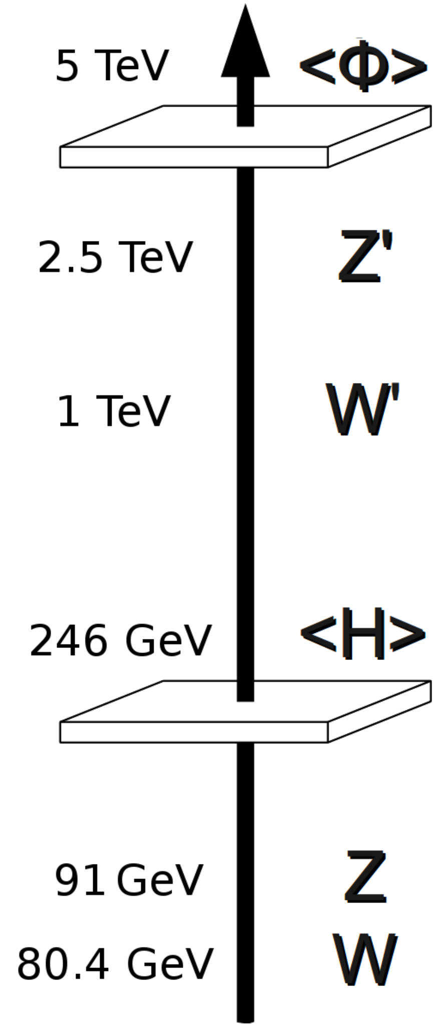
Need at least two scalars:

1. First, to break $SU(2)_R \times U(1)_X$:
   $\Rightarrow$ $SU(2)_R$ doublet with VEV
   $\langle \Phi \rangle = (0, f/\sqrt{2})$

2. Then, to generate fermion masses:
   Complex bidoublet Higgs with charges $(2,2)_0$ and VEV

$$\langle H \rangle = v/\sqrt{2} \begin{pmatrix} \cos\beta & 0 \\ 0 & \sin\beta \end{pmatrix}$$

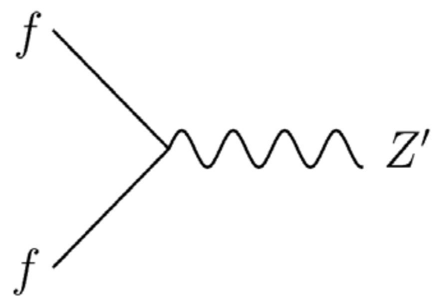
$\Rightarrow$ 2 Higgs doublets at EWSB scale

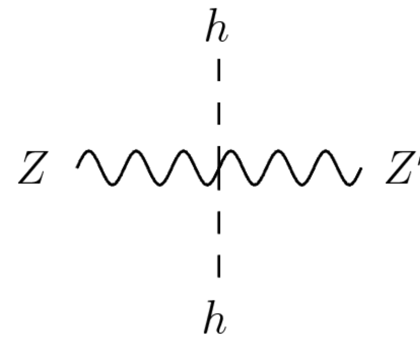


Effective Lagrangian with Higgs Bidoublet

- Gauge boson mixing:

$$Z' = c_r W_R^3 - s_r X$$





- Fermion couplings:

$$J^{\mu}_{Z'}(f) = \frac{1}{2} \sum_f f^\dagger \bar{\sigma}^\mu \left(g_r c_r T_R^3 - g_x s_r [B - L] \right) f,$$

- Higgs coupling: Only VEV enters EW fit
  $\Rightarrow$ Higgs sector can be represented by single field

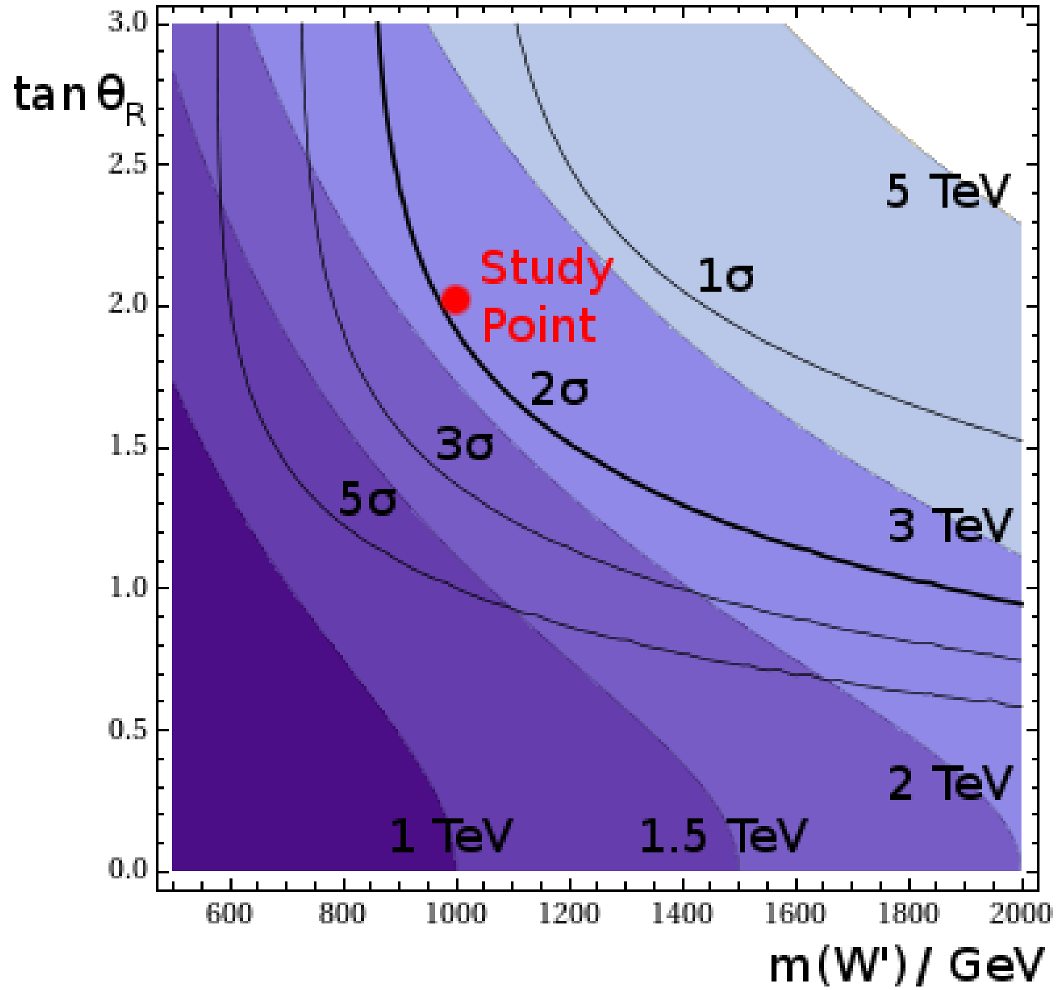
$$J^{\mu}_{Z'}(h) = c_r g_r \left[i(h^\dagger D^\mu h) + \mathrm{h.c.} \right].$$

Exclusion Plot for LR Model with Higgs Bifundamental

1. Higgs couples only to $SU(2)_R$
2. EW precision favors large $U(1)$ coupling constant
3. Large mass splitting between Z' and W'

Model point with minimal W' mass at SM+2σ:

$M(W') \approx 1$ TeV
$M(Z') \approx 2\text{-}3$ TeV



The first two years at the LHC...

W' search

$\sigma \times BR(e\nu) = 235$ fb

$\sigma \times BR(tb) = 700$ fb

What to expect:

- First $W' \to e\nu$ event in September 2010 (10/pb)
- By February 2011: Clear signal (100/pb)
- LHC shutdown: (1/fb) W' mass, BRs measured to ± 10 percent

Z' search

$\sigma \times BR(e^+e^-) = 0.6$ fb

$\sigma \times BR(t\bar{t}) = 0.1$ fb

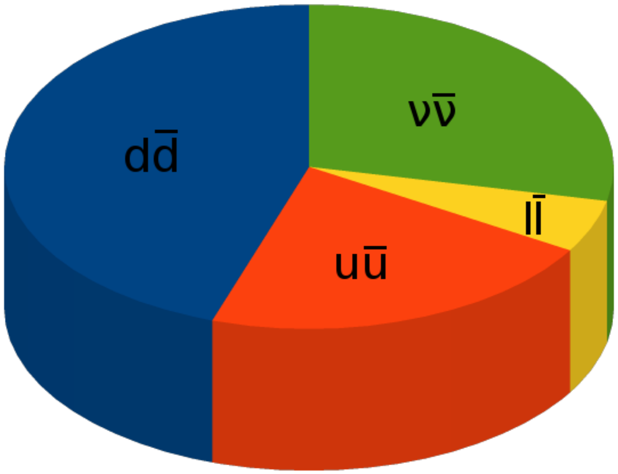
Alternative Higgs sector in the LR Model

How can we give the Z' groups something to do?

$\Rightarrow$ Higgs doublet with non-zero "B-L" charge ($X = 1/2$)

- T parameter and Z BRs: Favors small tan θ_r
- Four fermion operators: Same as previous analysis
- Optimal mixing angle: Much smaller than before

BUT: Z' BR to $\ell\bar{\ell}$ small



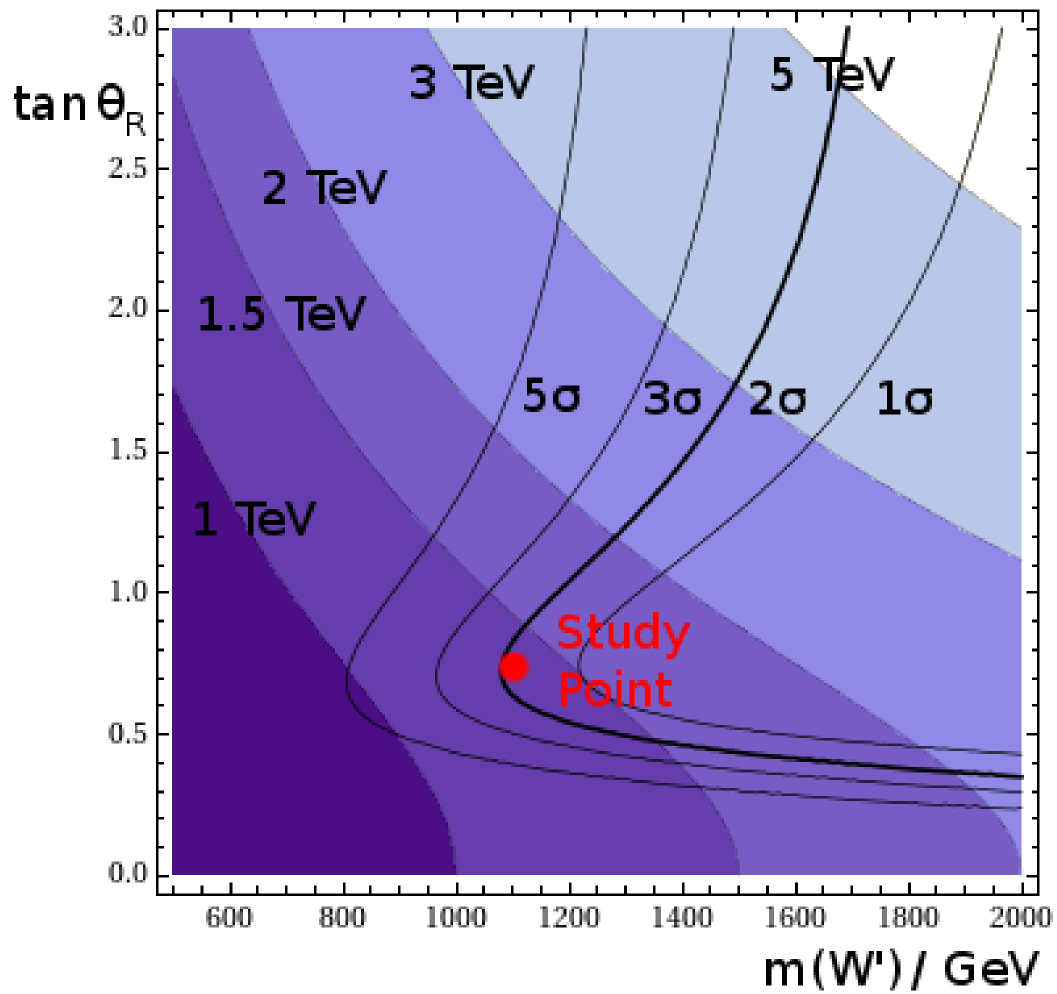
Disadvantage: Non-renormalizable Yukawa couplings.

Exclusion Plot For LR Model With Single Higgs

1. Higgs couples only to $U(1)_X$
2. EW precision favors small $U(1)$ coupling constant
3. Small mass splitting between Z' and W'

Model point with minimal W' mass at SM+2σ:

$M(W') \approx 1.1$ TeV
$M(Z') \approx 1.4$ TeV



What will the LHC find in this Case?

W' search

$\sigma \times BR(e\nu) = 330$ fb

$\sigma \times BR(tb) = 1$ pb

What to expect:

- First $W' \to e\nu$ event in August 2010 (5/pb)
- By November: Clear signal (30/pb)
- LHC shutdown: (1/fb) W' mass, BRs measured at few percent level

Z' search

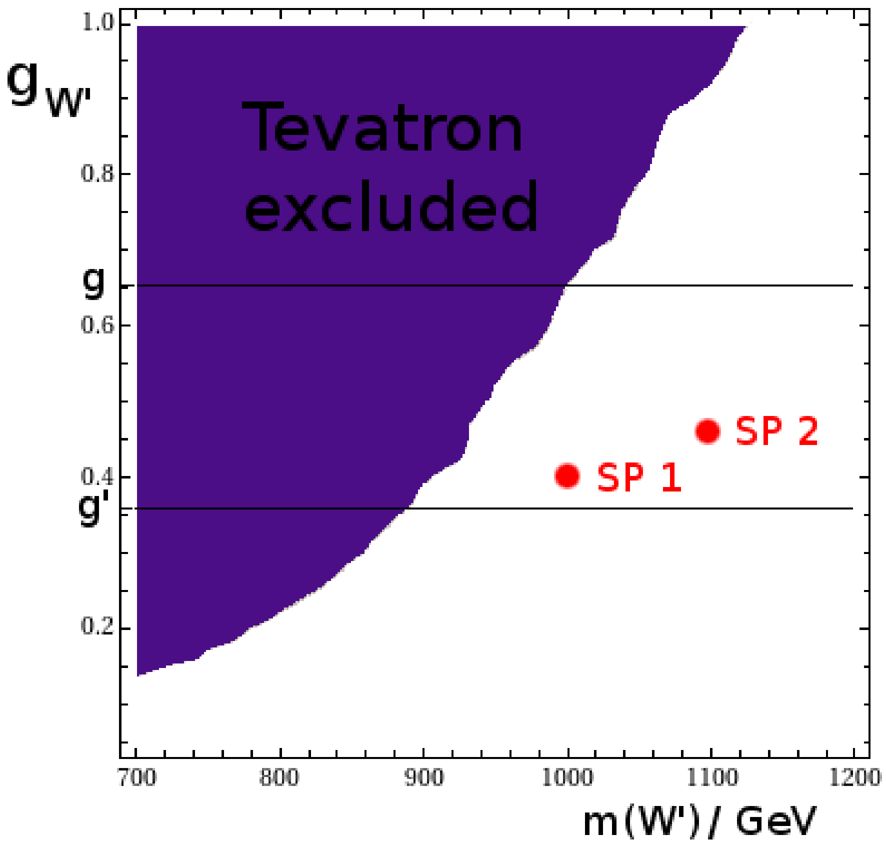
$\sigma \times BR(e^+e^-) = 5$ fb

$\sigma \times BR(t\bar{t}) = 20$ fb

Some events with 1/fb!

Tevatron Exclusion Limit

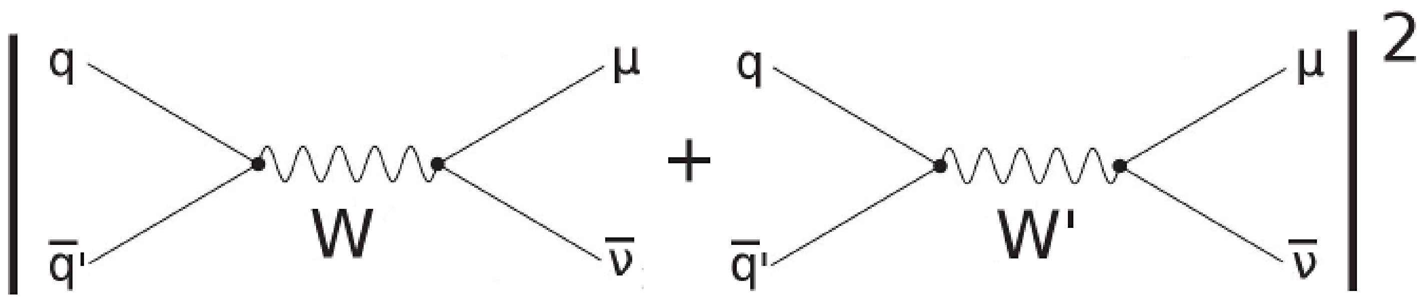
$W' \to e\nu$ searches at the Tevatron:



$$g_{W'} = g \;\Rightarrow\; M_{W'} > 1 \text{ TeV}.$$

- Search for isolated electron, no hard jets and missing E_T
- Demand >3 signal events with $m_t > 500$ GeV

How to tell Left- and Righthanded W primes apart?



- Lefthanded W': Same initial and final state, interference.
- Righthanded W': No interference with W boson.

For intermediate momentum, propagators have different signs:

$$P(W', W) \sim \frac{1}{p^2 - m^2}$$

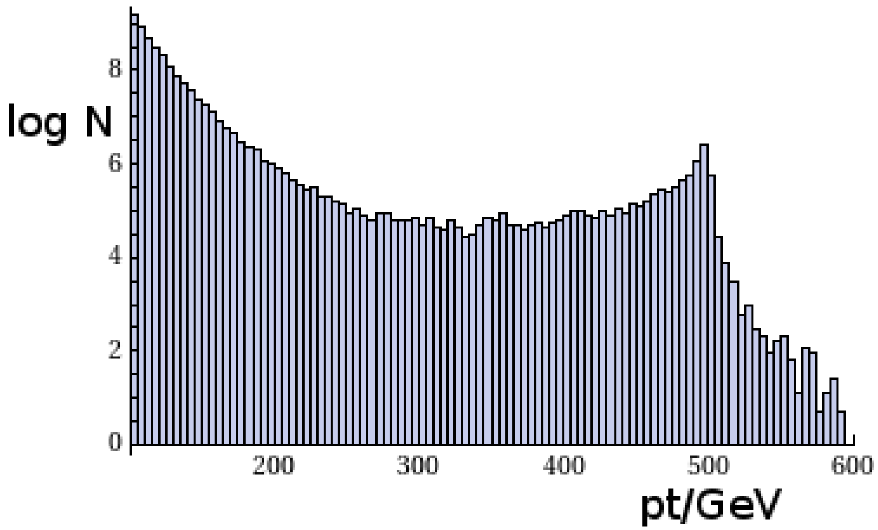
$\Rightarrow$ Destructive interference, LH W' peak more pronounced.
(see also T.Rizzo, 0704.0235).

MadGraph Simulation: W'_L vs. W'_R

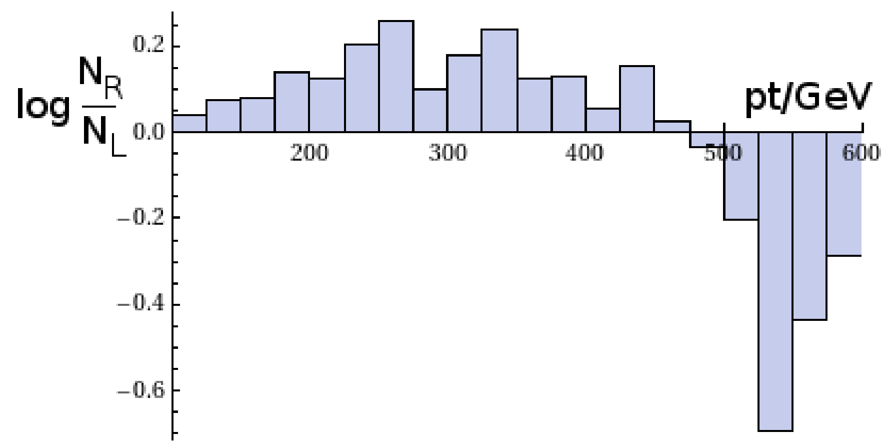
Can we see this effect? Simulate with MadGraph:
Toy model: 1 TeV W' with EW coupling strength

Plot lepton p_t distributions for 50/fb:

"Lefthanded" W':



R.H. W' / L.H. W':



$\Rightarrow$ Distributions show expected interference pattern.

Why Not Simulate With Pythia?

From Pythia 8 manual:

The *W'^+-* implementation is less ambitious than the *Z'^0*. Specifically, while indirect detection of a *Z'^0* through its interference contribution is a possible discovery channel in lepton colliders, there is no equally compelling case for *W^+-/W'^+-* interference effects being of importance for discovery, and such interference has therefore not been implemented for now. Related to this, a *Z'^0* could appear on its own in a new *U(1)* group, while *W'^+-* would have to sit in a *SU(2)* group and thus have a *Z'^0* partner that is likely to be found first. Only one process is implemented but, like for the *W^+-*, the ISR showers contain automatic matching to the *W'^+-* + 1 jet matrix elements.

Two More Random Observations

Some more things we learned while doing this analysis:

- Another way to split Z' and W' masses:

  Larger scalar representations for breaking $SU(2)_R$.

  E.g. complex scalar in RH isospin S multiplet:
  $\Rightarrow \rho_R = 1/\sqrt{2S}$.

- Adding more Z primes:
  - Generically: Reduces quality of EWP fit
  - Can compensate/improve by adjusting couplings
  - Requires significant fine-tuning of charges

Summary

1. For the early LHC, only righthanded W primes are relevant
2. The minimal model with an early W prime at the LHC is $SU(2)_L \times SU(2)_R \times U(1)_X$
3. With bidoublet scalar, expect large Z'/W' mass splitting, lots of W' events and no sign of a Z'
4. Interference effects with the W can possibly be used to distinguish W's from $SU(2)_L$ and $SU(2)_R$, and test our prediction